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Sensitivity of the SHiP experiment to Heavy Neutral Leptons

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Abstract: Heavy Neutral Leptons (HNLs) are hypothetical particles predicted by many extensions of the Standard Model. These particles can, among other things, explain the origin of neutrino masses, generate the observed matter-antimatter asymmetry in the Universe and provide a dark matter candidate. The SHiP experiment will be able to search for HNLs produced in decays of heavy mesons and travelling distances ranging between O (50 m) and tens of kilometers before decaying. We present the sensitivity of the SHiP experiment to a number of HNL's benchmark models and provide a way to calculate the SHiP's sensitivity to HNLs for arbitrary patterns of flavour mixings. The corresponding tools and data files are also made publicly available.

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Sensitivity of the SHiP experiment to Heavy Neutral Leptons



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ABSTRACT: Heavy Neutral Leptons (HNLs) are hypothetical particles predicted by many extensions of the Standard Model. These particles can, among other things, explain the origin of neutrino masses, generate the observed matter-antimatter asymmetry in the Universe and provide a dark matter candidate.

The SHiP experiment will be able to search for HNLs produced in decays of heavy mesons and travelling distances ranging between $\mathcal{O}(50\text{ m})$ and tens of kilometers before decaying. We present the sensitivity of the SHiP experiment to a number of HNL’s benchmark models and provide a way to calculate the SHiP’s sensitivity to HNLs for arbitrary patterns of flavour mixings. The corresponding tools and data files are also made publicly available.

KEYWORDS: Beyond Standard Model, Fixed target experiments

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1 The SHiP experiment and Heavy Neutral Leptons

The SHiP experiment. The Search for Hidden Particles (SHiP) experiment [1–4] is a new general purpose fixed target facility proposed at the CERN Super Proton Synchrotron (SPS) accelerator to search for long-lived exotic particles with masses between few hundred MeV and few GeV. These particles are expected to be predominantly produced in the decays of heavy hadrons. The facility is therefore designed to maximise the production and detector acceptance of charm and beauty mesons, while providing the cleanest possible environment. The 400 GeV proton beam extracted from the SPS will be dumped on a high density target with the aim of accumulating 2×10^{20} protons on target during 5 years of operation. The charm production at SHiP exceeds that of any existing and planned facility.

A dedicated detector, based on a long vacuum tank followed by a spectrometer and by particle identification detectors, will allow probing a variety of models with light long-lived exotic particles. Since particles originating in charm and beauty meson decays are produced with a significant transverse momentum with respect to the beam axis, the detector should be placed as close as possible to the target. A critical component of SHiP is therefore the muon shield [5], which deflects away from the detector the high flux of muons produced in the target, that would otherwise represent a very serious background for hidden particle searches. To suppress the background from neutrinos interacting in the fiducial volume, the decay volume is maintained under vacuum [3]. The detector is designed to reconstruct the exclusive decays of hidden particles and to reduce the background to less than 0.1 events in the sample of 2×10^{20} protons on target [4]. The detector consists of a large magnetic spectrometer located downstream of a 50 m long and 5×10 m wide decay volume. The spectrometer is designed to accurately reconstruct the decay vertex, mass and impact parameter of the decaying particle with respect to the target. A set of calorimeters followed by muon chambers provide identification of electrons, photons, muons

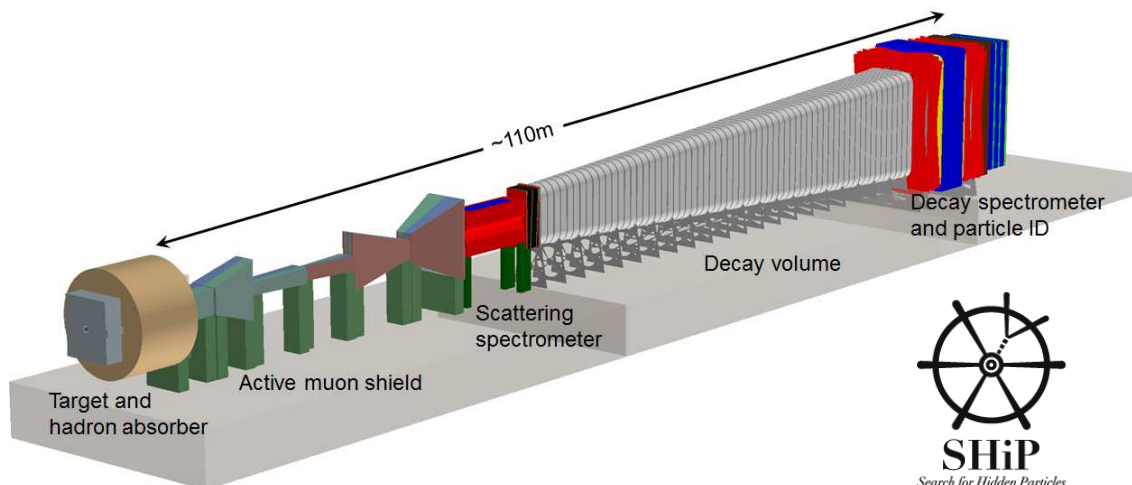


Figure 1. Overview of the SHiP experimental facility.

and charged hadrons. A dedicated timing detector measures the coincidence of the decay products, which allows the rejection of combinatorial background.

The decay volume is surrounded by background taggers to tag neutrino and muon inelastic scattering in the surrounding structures, which may produce long-lived neutral Standard Model particles, such as K_L , that have similar topologies to the expected signal.

The experimental facility is also ideally suited for studying the interactions of tau neutrinos. It will therefore host an emulsion cloud chamber based on the Opera concept, upstream of the hidden particle decay volume, followed by a muon spectrometer. The SHiP facility layout is shown in figure 1. Recent progress report [4] outlines the up-to-date experimental design as well as describes changes since the initial technical proposal [2].

Heavy Neutral Leptons. Among hypothetical long-lived particles that can be probed by the SHiP experiment are Heavy Neutral Leptons (or HNLs) [6]. The idea that HNLs — also known as right-handed, Majorana or sterile neutrinos — can be responsible for the smallness of neutrino masses goes back to the 1970s [7–12]. It has subsequently been understood that the same particles could be responsible for the generation of the matter-antimatter asymmetry of the Universe [13]. The idea of this scenario, called leptogenesis, was developed since the 1980s (see reviews [14–19] and references therein). In particular, it was found that the Majorana mass scale of right-handed neutrinos can be as low as $\mathcal{O}(\text{GeV})$ [20–22], thus providing a possibility for a leptogenesis scenario to be probed at a particle physics laboratory in the near future.

It was demonstrated in 2005 that by adding just three HNLs to the Standard Model one could not only explain neutrino oscillations and the origin of the baryon asymmetry of the Universe, but also provide a dark matter candidate [21, 23]. Two of the HNLs should have masses in the GeV range, see [24] for a review. This model, dubbed Neutrino Minimal Standard Model (or νMSM), is compatible with all the measurements so far performed by accelerator experiments and at the same time provides a solution for the puzzles of modern

physics [24, 25]. This made models with GeV scale HNLs a subject of intensive theoretical studies in the recent years [19, 26–45].

HNLs are massive Majorana particles that possess neutrino-like interactions with W and Z bosons (the interaction with the Higgs boson does not play a role in our analysis and will be ignored). The interaction strength is suppressed compared to that of ordinary neutrinos by flavour dependent mixing angles $U_\alpha \ll 1$ ($\alpha = \{e, \mu, \tau\}$). Thus, even the simplest HNL model contains 4 parameters: the HNL mass M_N and 3 mixing angles U_α^2 .¹ The idea of experimental searches for such particles goes back to the 1980s (see e.g. [46–50]) and a large number of experiments have searched for them in the past (see review of the past searches in [51–53]). HNLs are being searched at currently running experiments, including LHCb, CMS, ATLAS, T2K, Belle and NA62 [54–61].

The sensitivity of the SHiP experiment to HNLs was previously explored for several benchmark models [2, 65, 66] assuming particular ratios between the three HNL mixing angles [51]. This paper updates the previous results in a number of important ways. A recent work [67] revised the branching ratios of HNL production and decay channels. In addition, the estimates of the numbers of D - and B -mesons now include cascade production [64]. We update the lower limit of the SHiP sensitivity region and also evaluate the upper bound for the first time. We discuss potential impact of HNL production from B_c mesons. Moreover, our current sensitivity estimates are not limited to a set of benchmark models. Rather, we compute a *sensitivity matrix* — a model-independent tool to calculate the SHiP sensitivity for any model of HNL flavour mixings.

The paper is organised as follows. Section 2 describes the simulation of HNL events. The resulting sensitivity curves for mixing with each individual flavour, for the benchmark models of ref. [2] as well as the sensitivity matrix — are discussed in section 3. We present our method to evaluate the SHiP sensitivity to HNLs in a model-independent way in section 4 and conclude in section 5.

2 Monte Carlo simulation of heavy neutral leptons at SHiP

A detailed Monte Carlo simulation suite for the SHiP experiment, **FairShip**, was developed based on the **FairRoot** software framework [69]. In **FairShip** simulations primary collisions of protons are generated with **Pythia 8** [70] and the subsequent propagation and interactions of particles simulated with **GEANT4** [71]. Neutrino interactions are simulated with **GENIE** [72]; heavy flavour production and inelastic muon interactions with **Pythia 6** [73] and **GEANT4**. Secondary heavy flavour production in cascade interactions of hadrons originated by the initial proton collision [64] is also taken into account, which leads to an increase of the overall HNL production fraction (see table 1). The SHiP detector response is simulated using **GEANT4**. The pattern recognition algorithms applied to the hits on the straw spectrometer are described in [74], and the algorithms for particle identification are presented in [75].

¹The mixing angles U_α are in general complex numbers. However, the properties of HNLs that are important for us depend only on $|U_\alpha|$. Throughout this work we will write U_α^2 instead of $|U_\alpha|^2$ for compactness.

pN cross-section σ_{pN} [2]	$\bar{c}c$ fraction $X_{\bar{c}c}$ [62]	$\bar{b}b$ fraction $X_{\bar{b}b}$ [63]	Cascade enhancement f_{cascade}	
			charm [64]	beauty [64]
10.7 mb	1.7×10^{-3}	1.6×10^{-7}	2.3	1.7

Table 1. Charm and beauty production fractions and cascade enhancement factors for the SHiP experiment. Cross-section σ_{pN} is an average proton-nucleon inelastic cross-section for the molybdenum target [2].

The simulation takes the HNL mass M_N and its three flavour mixings U_e^2 , U_μ^2 , U_τ^2 as input parameters. For the pure HNLs mixing to a single SM flavour, the number of detected HNL events N_{events} is estimated as²

$$N_{\text{events}} = N_{\text{prod}} \times P_{\text{det}} \quad (2.1)$$

where N_{prod} is the number of produced HNLs that fly in the direction of the fiducial volume and P_{det} is the probability of HNL detection in the Hidden Sector detector. The number of produced HNLs is

$$N_{\text{prod}} = \sum_{q \in (c,b)} N_q \times \sum_h f(q \rightarrow h) \times \text{BR}(h \rightarrow N + X) \times \epsilon_{\text{decay}}, \quad (2.2)$$

where $f(q \rightarrow h)$ is the h meson production fraction³ at SHiP (see table 2), $\text{BR}(h \rightarrow N + X)$ is the mass dependent inclusive branching ratios for h mesons decays with HNL in the final state and ϵ_{decay} is the *geometrical acceptance* — the fraction of produced HNLs that fly into direction of the fiducial volume. Figure 2 shows the product between the meson production fraction and its inclusive decay branching fraction into sterile neutrinos. Finally, N_q is the total number of produced quarks and antiquarks of the given flavour q taking into account the quark-antiquark production fraction $X_{\bar{q}q}$ and the cascade enhancement factor f_{cascade} given in table 1,

$$N_q = 2 \times X_{\bar{q}q} \times f_{\text{cascade}} \times N_{\text{POT}}. \quad (2.3)$$

The HNL *detection probability* is given by

$$P_{\text{det}} = P_{\text{decay}} \times \text{BR}(N \rightarrow \text{visible}) \times \epsilon_{\text{det}}, \quad (2.4)$$

where $\text{BR}(N \rightarrow \text{visible})$ is the total HNL decay branching ratio into visible channels (see HNL decay channels in appendix A), P_{decay} is the probability that the HNL decays inside the fiducial volume,

$$P_{\text{decay}} = \exp\left(-\frac{l_{\text{ini}}}{l_{\text{decay}}}\right) - \exp\left(-\frac{l_{\text{fin}}}{l_{\text{decay}}}\right), \quad (2.5)$$

²The case of the general mixing ratio is discussed in section 4.

³The meson production fraction is the probability that a quark of a given flavour hadronizes into the given meson. In the sum over hadrons we consider only lightest hadrons of a given flavour that have only weak decays. Higher resonances have negligible branching to HNLs as they mostly decay via strong interactions.

meson	$f(q \rightarrow \text{meson})$	meson	$f(q \rightarrow \text{meson})$
D^+	0.207	B^+	0.417
D^0	0.632	B^0	0.418
D_s	0.088	B_s	0.113
J/ψ	0.01	B_c	$\leq 2.6 \times 10^{-3}$

Table 2. Production fraction and expected number of different mesons in SHiP taking into account cascade production [68]. For $f(b \rightarrow B_c)$ see text for details.

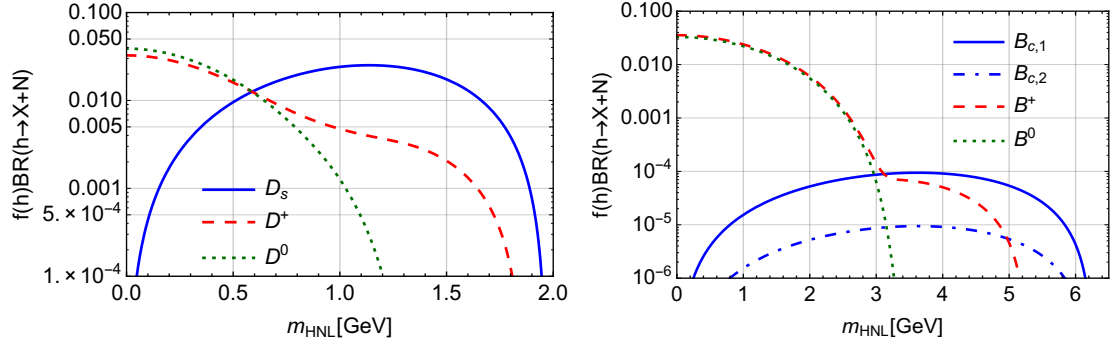


Figure 2. HNL production branching ratios multiplied with the production fraction of the meson decaying into HNL, for charm (left) and beauty (right) mesons [67]. The mixing angles have been set to $U_e^2 = 1$, $U_\mu^2 = U_\tau^2 = 0$. The production from D^+ and B^+ remains relevant for higher masses for D^0 and B^0 because of the fully leptonic decays $h^+ \rightarrow N + \ell^+$. The B_c production fraction is unknown (see text for details) and we show two examples: $f(b \rightarrow B_c) = 2 \times 10^{-3}$ ($B_{c,1}$ line) and $f(b \rightarrow B_c) = 2 \times 10^{-4}$ ($B_{c,2}$ line).

where l_{ini} is the distance travelled by HNL before it entered the decay vessel; l_{fin} is the distance to the end of the decay vessel along the HNL trajectory; $l_{\text{decay}} = c\gamma\tau_N$ is the HNL decay length (γ and τ_N being HNL gamma factor and proper lifetime). Finally, ϵ_{det} is the efficiency of detecting the charged daughters of the decaying HNL. It takes into account the track reconstruction efficiency and the selection efficiency, further described in [2, 65, 75]. In order to distinguish the signal candidates from possible SM background, we put a criteria that at least two charged tracks reconstructed to the decay point are present. The reconstruction efficiencies for the decay channels $N \rightarrow \mu\mu\nu$ and $N \rightarrow \mu\pi$ are given in e.g. [2, section 5.2.2.2]. Using FairShip, a scan was done over the HNL parameter space. For each set of HNL parameters we ran a simulation with 300 HNL events, produced randomly from decay of mesons. We determined P_{decay} , ϵ_{decay} and ϵ_{det} in each of them and average over simulations to find the expected number of detected events, \bar{N}_{events} .

For HNLs with masses $M_N \lesssim 500 \text{ MeV}$ kaon decays are the dominant production channel. While $\mathcal{O}(10^{20})$ kaons are expected at SHiP, most of them are stopped in the target or hadron stopper before decaying. As a consequence, only HNLs originating from charm and beauty mesons are included in the estimation of the sensitivity. SHiP can however explore the νMSM parameter space down to the constraints given by Big Bang

nucleosynthesis observations [76, 77], even with this conservative assumption. It is expected that the NA62 experiment will also probe the region below the kaon mass [78].

For HNL masses $M_N \gtrsim 3 \text{ GeV}$ the contribution of B_c mesons to the HNL production can be relevant because the $B_c^+ \rightarrow N + \ell^+$ decay width is proportional to the CKM matrix element $|V_{cb}|^2$, while the decays of B^+ are proportional to $|V_{ub}|^2$ [51, 67]. The ratio $|V_{cb}|^2/|V_{ub}|^2 \sim 10^2$, which explains the relative importance of B_c channels even for small production fraction $f(b \rightarrow B_c)$. This production fraction has not been measured at the SHiP center of mass energy. If the B_c production fraction at SHiP is at the LHC level, its contribution will be dominant. However, at some unknown energy close to the B_c mass this production fraction becomes negligible. The existing Tevatron measurement place $f(b \rightarrow B_c) = 2.08_{-0.95}^{+1.06} \times 10^{-3}$ at $\sqrt{s} = 1.8 \text{ TeV}$ [79]. More recent LHCb measurement at $\sqrt{s} = 7$ and 8 TeV gave $f(b \rightarrow B_c)/f(b \rightarrow B^+) = 0.008 \pm 0.004$ [80]. Using $f(b \rightarrow B^+) = 0.33$ from the LHCb measurement performed at $\sqrt{s} = 7 \text{ TeV}$ [81], one obtains $f(b \rightarrow B_c) = 2.6 \times 10^{-3}$. Theoretical evaluations have mostly been performed for TeV energies (see e.g. [82–85]) with the exception of the works [86, 87] that computed the production fraction down to energies of tens of GeV (where they found the fraction to be negligible). However, by comparing predictions of [87] with LHCb or Tevatron measurements, we see that (i) it underpredicts the value of $f(b \rightarrow B_c)$ by about an order of magnitude at these energies and (ii) it predicts stronger than observed change of the production fraction between LHC and Tevatron energies. Therefore we have to treat $f(b \rightarrow B_c)$ as an unknown parameter somewhere between its LHC value and zero and provide two estimates: an optimistic estimate for which $f(b \rightarrow B_c)$ is at the LHC level and a pessimistic estimate where we do not include B_c mesons at all. In the simulation we take the angular distribution of B_c mesons to be the same as that of B^+ mesons, based on comparisons performed with the BCVEGPY [88] and FONLL [89, 90] packages, while we rescale the energy distribution according to the meson mass.

Detailed background studies have proven that the yield of background events passing the online and offline event selections is negligible [2]. Therefore, the 90% confidence region is defined as the region of the parameter space where one expects on average $\bar{N}_{\text{events}} \geq 2.3$ reconstructed HNL events, corresponding to the discovery threshold with an expected background yield of 0.1 events.

3 SHiP sensitivity for benchmark HNL models

Figure 3 presents the 90% C.L. sensitivity curves for HNLs mixing to only one SM flavour. The sensitivity curves have a characteristic “cigar-like shape” for masses $M_N > 2 \text{ GeV}$. The *upper boundary* is determined by the condition that the decay length of a produced particle becomes comparable with the distance between the target and the decay volume, and therefore the HNLs produced at the target may not reach the decay volume, see eq. (2.5). For masses $M_N < 2 \text{ GeV}$ such an upper boundary also exists, but it is outside the plot range, owing to a much larger number of parent D mesons. The *lower boundary* of the sensitivity region is determined by the parameters at which decays become too rare

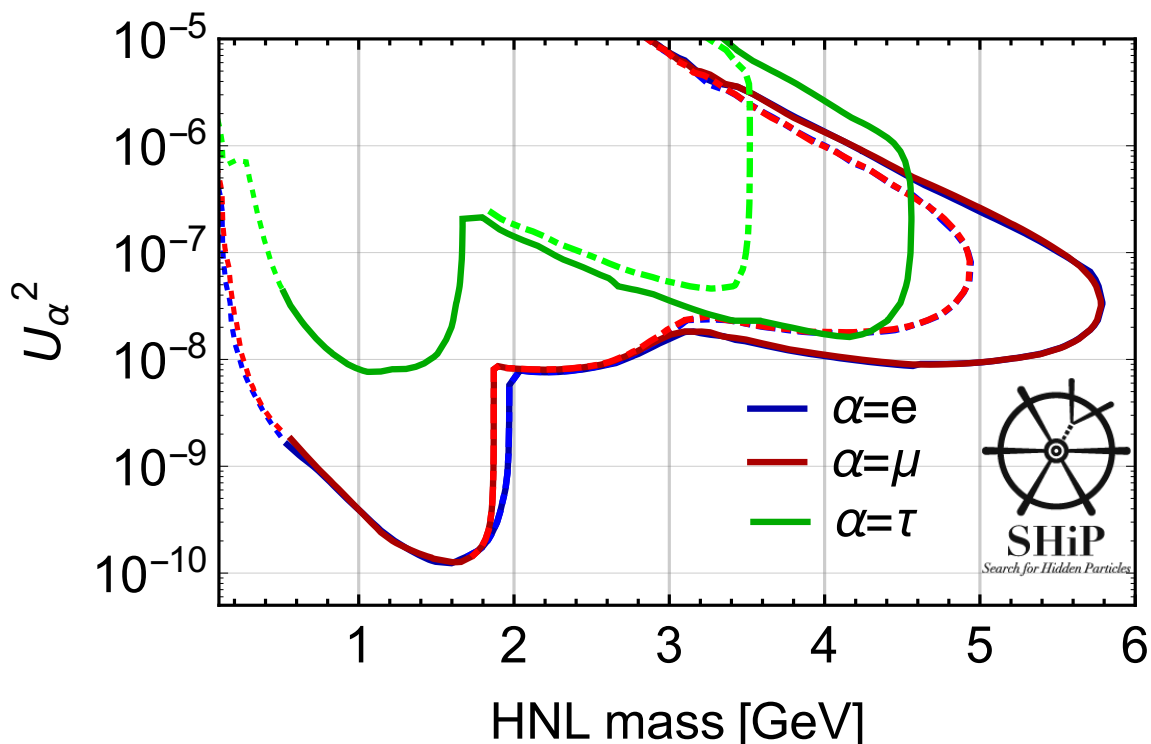


Figure 3. SHiP sensitivity curves (90% CL) for HNLs mixing to a single SM flavour: electron (blue), muon (red) and tau (green). To indicate the uncertainty related to the unknown production fraction of B_c meson (see text for details), we show two types of curve for each flavour. Solid curves show the sensitivity contours when the production fraction of B_c mesons equals to that at LHC energies: $f(b \rightarrow B_c) = 2.6 \times 10^{-3}$. Dashed-dotted lines do not include contributions from B_c . Below 0.5 GeV only production from D and B mesons is included (dotted lines).

(decay length much larger than the detector size). The intersection of the upper and lower boundaries defines the *maximal mass* which can be probed at the experiment.

We also provide updated sensitivity estimates for the three benchmark models I–III presented in the Technical Proposal [2, 65]. These models allow to explain neutrino flavour oscillations while at the same time maximizing the mixing to one particular flavour, and are defined by the following ratios of flavour couplings [51]:

- I. $U_e^2 : U_\mu^2 : U_\tau^2 = 52 : 1 : 1$
- II. $U_e^2 : U_\mu^2 : U_\tau^2 = 1 : 16 : 3.8$
- III. $U_e^2 : U_\mu^2 : U_\tau^2 = 0.061 : 1 : 4.3$

The sensitivity curves for these models are shown in figure 4.

4 Model independent SHiP sensitivity

In this section we provide an efficient way to estimate the SHiP sensitivity to an HNL model with an arbitrary ratio $U_e^2 : U_\mu^2 : U_\tau^2$. It is based on the observation that the dependence

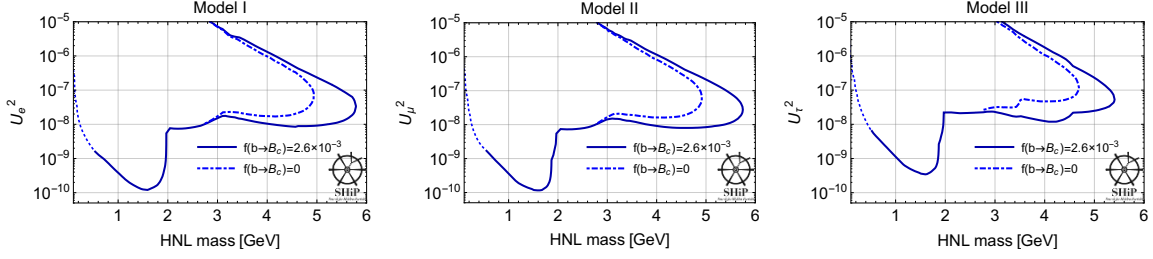


Figure 4. Sensitivity curves for 3 benchmark models I–III (90%CL). Individual curves are explained in figure 3.

of the number of events, N_{events} , on the mass and mixing angles of HNL factorizes, and therefore all relevant information can be extracted from a handful of simulations, rather than from a scan over an entire 4-dimensional HNL parameter space ($M_N, U_e^2, U_\mu^2, U_\tau^2$).

All information about the HNL production in a particular experiment is contained in $N_\alpha(M_N)$ — the number of HNLs that would be produced through all possible channels with the mixings $U_\alpha^2 = 1$ and $U_{\beta \neq \alpha}^2 = 0$:

$$N_\alpha \equiv \sum_{\text{hadrons } h} N_h \sum_{\text{channels}} \text{BR}(h \rightarrow N + X_\alpha) \epsilon_{\text{decay}, \alpha} \Big|_{U_\alpha^2=1; U_{\beta \neq \alpha}^2=0} \quad (4.1)$$

Here N_h is the number of hadrons of a given type h , $\text{BR}(h \rightarrow N + X_\alpha)$ is the branching ratio for their decay into an HNL plus any number of other particles X_α with total lepton flavour number $L_\alpha = 1$ and $\epsilon_{\text{decay}, \alpha}$ is the geometrical acceptance of HNL that in general depends not only on the mass but also on the flavour. The overall number of HNLs (given by eq. (2.2)) produced via the mixing with the flavour α and flying in the direction of the decay vessel is given by

$$N_{\text{prod}, \alpha}(M_N | \vec{U}^2) = U_\alpha^2 N_\alpha(M_N). \quad (4.2)$$

The decay probability P_{decay} should be treated differently, depending on the ratio of the decay length and the distance from the target to the decay vessel. It also depends on the production channel through the mean gamma factor γ_α entering the decay length.

In the limit when the decay length much larger than the distance between the beam target and the exit lid of the SHiP decay volume, the U_β^2 dependence of the decay probability can be accounted for similarly to eq. (4.2):

$$P_{\text{decay}, \alpha}^{\text{linear}}(M_N | \vec{U}^2) = \frac{l_{\text{fin}} - l_{\text{ini}}}{\gamma_\alpha c \hbar} \sum_{\beta} U_\beta^2 \Gamma_\beta(M_N), \quad (4.3)$$

where Γ_β is a decay width of the HNL of mass M_N that has mixing angles $U_\beta^2 = 1$, $U_{\alpha \neq \beta}^2 = 0$, the definitions of lengths $l_{\text{ini}}, l_{\text{fin}}$ are given after eq. (2.5). The index α in eq. (4.3) indicates that the HNL was produced via mixing U_α^2 (although can decay through the mixing with any flavour), so γ_α is the mean gamma factor of HNLs produced through the mixing with the flavour α .

In the general case, when the decay length l_{decay} is not necessarily larger than l_{fin} , the analogous decay probability $P_{\text{decay},\alpha}$ can be expressed via (4.3) as follows:

$$P_{\text{decay},\alpha}(M_N|\vec{U}^2) = \left[\exp\left(-\frac{l_{\text{ini}}}{l_{\text{fin}} - l_{\text{ini}}} P_{\text{decay},\alpha}^{\text{linear}}(M_N|\vec{U}^2)\right) - \exp\left(-\frac{l_{\text{fin}}}{l_{\text{fin}} - l_{\text{ini}}} P_{\text{decay},\alpha}^{\text{linear}}(M_N|\vec{U}^2)\right) \right] \times \text{BR}(N \rightarrow \text{visible}), \quad (4.4)$$

where $\text{BR}(N \rightarrow \text{visible})$ is the probability that the HNL decays into the final states detectable by SHiP.

Finally, we define the HNL detection efficiency as

$$\epsilon_{\text{det}}(M_N|\vec{U}^2) = \sum_{\beta} \text{BR}(N \rightarrow X_{\beta}) \times \epsilon_{\text{det},\beta}, \quad (4.5)$$

where $\text{BR}(N \rightarrow X_{\beta})$ is the branching ratio of a decay through the mixing angle β and $\epsilon_{\text{det},\beta}$ is the probability that the HNL decay products are successfully detected.

As a result, the number of detected events is given by

$$N_{\text{decay}}(M_N|\vec{U}^2) = \sum_{\alpha} N_{\text{prod},\alpha}(M_N|\vec{U}^2) P_{\text{decay},\alpha}(M_N|\vec{U}^2) \epsilon_{\text{det}}(M_N|\vec{U}^2). \quad (4.6)$$

We see that it is sufficient to know 9 functions of the HNL mass — $N_{\alpha}(M_N)$, $P_{\text{decay},\alpha}^{\text{linear}}(M_N)$ and $\epsilon_{\text{det},\alpha}(M_N)$ — to determine the number of detected events for any combination of the mixing angles.

To determine these numbers we ran 9 Monte Carlo simulations for each mass. We first ran 3 simulations with vectors $\vec{U}^2 = (x, 0, 0)$, $\vec{U}^2 = (0, x, 0)$, $\vec{U}^2 = (0, 0, x)$, where x is any sufficiently small number such that $l_{\text{decay}} \gg l_{\text{det}}$. We then ran a set of 6 non-physical simulations, where a particle is produced solely via channel α and decays solely through the channel $\beta \neq \alpha$. Using results of these simulations we extract N_{α} , P_{α} and $\epsilon_{\text{det},\alpha}$ values that allow us to generate the expected number of detected events for any values of masses and couplings.

The results are available at Zenodo platform [91] with instructions for reading the file and generating sensitivity curves at different confidence levels.

5 Conclusion

Using a detailed Monte Carlo simulation of HNL production in decays of charm and beauty mesons, and of the detector response to the signal generated by a decaying HNL, we calculated the sensitivity of the SHiP experiment to HNLs, updating the results presented in the Technical Proposal [2]. In particular, we assess the potential impact of HNL production from B_c mesons decay, showing its influence on the extent of the probed HNL mass range. We take into account cascade production of B and D mesons as well as revised estimates of branching ratios of HNL production and decay, and we extend our calculation to masses below ~ 500 MeV, where SHiP has a potential to fully explore the allowed region. Finally, we present our results as a publicly available dataset, providing a model-independent way to calculate the SHiP sensitivity for any pattern of HNL flavour mixings.

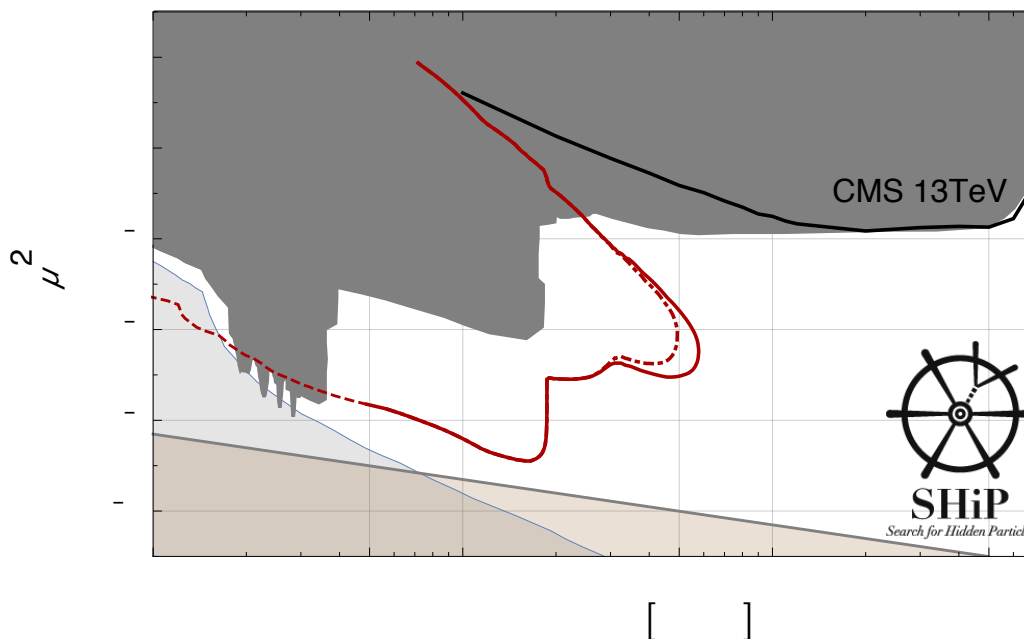


Figure 5. Parameter space of HNLs and potential reach of the SHiP experiment for the mixing with muon flavour. Dark gray area is excluded from previous experiments, see e.g. [6]. Black solid line is the recent bound from the CMS 13 TeV run [57]. Solid and dashed-dotted red lines indicate the uncertainty, related to the production fraction of B_c mesons at SHiP energies that has not been measured experimentally or reliably calculated (see section 2 for details). The sensitivity of SHiP below kaon mass (dashed line) is based on the number of HNLs produced in the decay of D -mesons only and does not take into account HNL production from kaon decays. The primordial nucleosynthesis bounds on HNL lifetime are from [76]. The seesaw line indicates the parameters obeying the seesaw relation $|U_\mu|^2 \sim m_\nu/M_N$, where for active neutrino mass we substitute $m_\nu = \sqrt{\Delta m_{\text{atm}}^2} \approx 0.05$ eV [6].

The SHiP experiment offers an increase of up to 3 orders of magnitude in the sensitivity to heavy neutral leptons, figure 5. It is capable of probing cosmologically interesting region of the HNL parameter space, and of potentially discovering the origin of neutrino masses and of the matter-antimatter asymmetry of the Universe.

Acknowledgments

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A HNL decays

For completeness we list the relevant HNL decay channels in table 3 (reproduced from [67]).

Channel	Opens at [MeV]	Relevant from [MeV]	Relevant up to [MeV]	Max BR [%]	Reference in [67]
$N \rightarrow \nu_\alpha \nu_\beta \bar{\nu}_\beta$	$\sum m_\nu \approx 0$	$\sum m_\nu \approx 0$	—	100	(3.5)
$N \rightarrow \nu_\alpha e^+ e^-$	1.02	1.29	—	21.8	(3.4)
$N \rightarrow \nu_\alpha \pi^0$	135	136	3630	57.3	(3.7)
$N \rightarrow e^- \pi^+$	140	141	3000	33.5	(3.6)
$N \rightarrow \mu^- \pi^+$	245	246	3000	19.7	(3.6)
$N \rightarrow e^- \nu_\mu \mu^+$	106	315	—	5.15	(3.1)
$N \rightarrow \mu^- \nu_e e^+$	106	315	—	5.15	(3.1)
$N \rightarrow \nu_\alpha \mu^+ \mu^-$	211	441	—	4.21	(3.4)
$N \rightarrow \nu_\alpha \eta$	548	641	2330	3.50	(3.7)
$N \rightarrow e^- \rho^+$	770	780	4550	10.4	(3.8)
$N \rightarrow \nu_\alpha \rho^0$	770	780	3300	4.81	(3.9)
$N \rightarrow \mu^- \rho^+$	875	885	4600	10.2	(3.8)
$N \rightarrow \nu_\alpha \omega$	783	997	1730	1.40	(3.9)
$N \rightarrow \nu_\alpha \eta'$	958	1290	2400	1.86	(3.7)
$N \rightarrow \nu_\alpha \phi$	1019	1100	4270	5.90	(3.9)
$N \rightarrow e^- D_s^{*+}$	2110	2350	—	3.05	(3.8)
$N \rightarrow \mu^- D_s^{*+}$	2220	2370	—	3.03	(3.8)
$N \rightarrow e^- D_s^+$	1970	2660	4180	1.23	(3.6)
$N \rightarrow \mu^- D_s^+$	2070	2680	4170	1.22	(3.6)
$N \rightarrow \nu_\alpha \eta_c$	2980	3940	—	1.26	(3.7)
$N \rightarrow \tau^- \nu_e e^+$	1780	3980	—	1.52	(3.1)
$N \rightarrow e^- \nu_\tau \tau^+$	1780	3980	—	1.52	(3.1)
$N \rightarrow \tau^- \nu_\mu \mu^+$	1880	4000	—	1.51	(3.1)
$N \rightarrow \mu^- \nu_\tau \tau^+$	1880	4000	—	1.51	(3.1)

Table 3. List of the relevant HNL decay channels with branching ratio above 1% covering the HNL mass range up to 5 GeV implemented in **FairShip**. The numbers are provided for $|U_e|^2 = |U_\mu|^2 = |U_\tau|^2$. For neutral current channels (with neutrinos in the final state) the sum over neutrino flavours is taken, otherwise the lepton flavour is shown explicitly. Columns: (1) the HNL decay channel. (2) The HNL mass at which the channel opens. (3) The HNL mass starting from which the channel becomes relevant (branching ratio of this channel exceeds 1%). For multimeson final states we provide our best-guess estimates. (4) HNL mass above which the channel contributes less than 1%, with “—” indicating that the channel is still relevant at $M_N = 5$ GeV. (5) The maximum branching ratio of the channel for $M_N < 5$ GeV. (6) Reference to the appropriate formula for decay width in ref. [67].

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References

- [1] W. Bonivento et al., *Proposal to Search for Heavy Neutral Leptons at the SPS*, [arXiv:1310.1762](#) [[INSPIRE](#)].
- [2] SHiP collaboration, *A facility to Search for Hidden Particles (SHiP) at the CERN SPS*, [arXiv:1504.04956](#) [[INSPIRE](#)].
- [3] SHiP collaboration, *The experimental facility for the Search for Hidden Particles at the CERN SPS*, *2019 JINST* **14** P03025 [[arXiv:1810.06880](#)] [[INSPIRE](#)].
- [4] SHiP collaboration, *SHiP Experiment — Progress Report*, [CERN-SPSC-2019-010](#).
- [5] SHiP collaboration, *The active muon shield in the SHiP experiment*, *2017 JINST* **12** P05011 [[arXiv:1703.03612](#)] [[INSPIRE](#)].
- [6] S. Alekhin et al., *A facility to Search for Hidden Particles at the CERN SPS: the SHiP physics case*, *Rept. Prog. Phys.* **79** (2016) 124201 [[arXiv:1504.04855](#)] [[INSPIRE](#)].
- [7] P. Minkowski, $\mu \rightarrow e\gamma$ at a Rate of One Out of 10^9 Muon Decays?, *Phys. Lett.* **67B** (1977) 421 [[INSPIRE](#)].
- [8] T. Yanagida, *Horizontal gauge symmetry and masses of neutrinos*, *Conf. Proc.* **C 7902131** (1979) 95 [[INSPIRE](#)].
- [9] S.L. Glashow, *The Future of Elementary Particle Physics*, *NATO Sci. Ser.* **B 61** (1980) 687 [[INSPIRE](#)].
- [10] M. Gell-Mann, P. Ramond and R. Slansky, *Complex Spinors and Unified Theories*, *Conf. Proc.* **C 790927** (1979) 315 [[arXiv:1306.4669](#)] [[INSPIRE](#)].
- [11] R.N. Mohapatra and G. Senjanović, *Neutrino Mass and Spontaneous Parity Nonconservation*, *Phys. Rev. Lett.* **44** (1980) 912 [[INSPIRE](#)].
- [12] R.N. Mohapatra and G. Senjanović, *Neutrino Masses and Mixings in Gauge Models with Spontaneous Parity Violation*, *Phys. Rev. D* **23** (1981) 165 [[INSPIRE](#)].
- [13] M. Fukugita and T. Yanagida, *Resurrection of grand unified theory baryogenesis*, *Phys. Rev. Lett.* **89** (2002) 131602 [[hep-ph/0203194](#)] [[INSPIRE](#)].
- [14] W. Buchmüller, P. Di Bari and M. Plümacher, *Leptogenesis for pedestrians*, *Annals Phys.* **315** (2005) 305 [[hep-ph/0401240](#)] [[INSPIRE](#)].
- [15] S. Davidson, E. Nardi and Y. Nir, *Leptogenesis*, *Phys. Rept.* **466** (2008) 105 [[arXiv:0802.2962](#)] [[INSPIRE](#)].
- [16] M. Shaposhnikov, *Baryogenesis*, *J. Phys. Conf. Ser.* **171** (2009) 012005 [[INSPIRE](#)].
- [17] A. Pilaftsis, *The Little Review on Leptogenesis*, *J. Phys. Conf. Ser.* **171** (2009) 012017 [[arXiv:0904.1182](#)] [[INSPIRE](#)].
- [18] M. Drewes et al., *ARS Leptogenesis*, *Int. J. Mod. Phys. A* **33** (2018) 1842002 [[arXiv:1711.02862](#)] [[INSPIRE](#)].

- [19] E.J. Chun et al., *Probing Leptogenesis*, *Int. J. Mod. Phys. A* **33** (2018) 1842005 [[arXiv:1711.02865](#)] [[INSPIRE](#)].
- [20] E.K. Akhmedov, V.A. Rubakov and A. Yu. Smirnov, *Baryogenesis via neutrino oscillations*, *Phys. Rev. Lett.* **81** (1998) 1359 [[hep-ph/9803255](#)] [[INSPIRE](#)].
- [21] T. Asaka and M. Shaposhnikov, *The nuMSM, dark matter and baryon asymmetry of the universe*, *Phys. Lett. B* **620** (2005) 17 [[hep-ph/0505013](#)] [[INSPIRE](#)].
- [22] M. Shaposhnikov, *The nuMSM, leptonic asymmetries and properties of singlet fermions*, *JHEP* **08** (2008) 008 [[arXiv:0804.4542](#)] [[INSPIRE](#)].
- [23] T. Asaka, S. Blanchet and M. Shaposhnikov, *The nuMSM, dark matter and neutrino masses*, *Phys. Lett. B* **631** (2005) 151 [[hep-ph/0503065](#)] [[INSPIRE](#)].
- [24] A. Boyarsky, O. Ruchayskiy and M. Shaposhnikov, *The Role of sterile neutrinos in cosmology and astrophysics*, *Ann. Rev. Nucl. Part. Sci.* **59** (2009) 191 [[arXiv:0901.0011](#)] [[INSPIRE](#)].
- [25] M. Shaposhnikov, *Is there a new physics between electroweak and Planck scales?*, in *Astroparticle Physics: Current Issues, 2007 (APCI07)*, Budapest, Hungary, June 21–23, 2007 (2007) [[arXiv:0708.3550](#)] [[INSPIRE](#)].
- [26] L. Canetti, M. Drewes and M. Shaposhnikov, *Matter and Antimatter in the Universe*, *New J. Phys.* **14** (2012) 095012 [[arXiv:1204.4186](#)] [[INSPIRE](#)].
- [27] M. Drewes and B. Garbrecht, *Leptogenesis from a GeV Seesaw without Mass Degeneracy*, *JHEP* **03** (2013) 096 [[arXiv:1206.5537](#)] [[INSPIRE](#)].
- [28] L. Canetti, M. Drewes, T. Frossard and M. Shaposhnikov, *Dark Matter, Baryogenesis and Neutrino Oscillations from Right Handed Neutrinos*, *Phys. Rev. D* **87** (2013) 093006 [[arXiv:1208.4607](#)] [[INSPIRE](#)].
- [29] L. Canetti, M. Drewes and M. Shaposhnikov, *Sterile Neutrinos as the Origin of Dark and Baryonic Matter*, *Phys. Rev. Lett.* **110** (2013) 061801 [[arXiv:1204.3902](#)] [[INSPIRE](#)].
- [30] B. Garbrecht, F. Gautier and J. Klaric, *Strong Washout Approximation to Resonant Leptogenesis*, *JCAP* **09** (2014) 033 [[arXiv:1406.4190](#)] [[INSPIRE](#)].
- [31] B. Shuve and I. Yavin, *Baryogenesis through Neutrino Oscillations: A Unified Perspective*, *Phys. Rev. D* **89** (2014) 075014 [[arXiv:1401.2459](#)] [[INSPIRE](#)].
- [32] L. Canetti, M. Drewes and B. Garbrecht, *Probing leptogenesis with GeV-scale sterile neutrinos at LHCb and Belle II*, *Phys. Rev. D* **90** (2014) 125005 [[arXiv:1404.7114](#)] [[INSPIRE](#)].
- [33] A.M. Gago, P. Hernández, J. Jones-Pérez, M. Losada and A. Moreno Briceño, *Probing the Type I Seesaw Mechanism with Displaced Vertices at the LHC*, *Eur. Phys. J. C* **75** (2015) 470 [[arXiv:1505.05880](#)] [[INSPIRE](#)].
- [34] T. Hambye and D. Teresi, *Higgs doublet decay as the origin of the baryon asymmetry*, *Phys. Rev. Lett.* **117** (2016) 091801 [[arXiv:1606.00017](#)] [[INSPIRE](#)].
- [35] P. Hernández, M. Kekic, J. López-Pavón, J. Racker and J. Salvado, *Testable Baryogenesis in Seesaw Models*, *JHEP* **08** (2016) 157 [[arXiv:1606.06719](#)] [[INSPIRE](#)].
- [36] A. Caputo, P. Hernández, M. Kekic, J. López-Pavón and J. Salvado, *The seesaw path to leptonic CP-violation*, *Eur. Phys. J. C* **77** (2017) 258 [[arXiv:1611.05000](#)] [[INSPIRE](#)].
- [37] J. Ghiglieri and M. Laine, *Neutrino dynamics below the electroweak crossover*, *JCAP* **07** (2016) 015 [[arXiv:1605.07720](#)] [[INSPIRE](#)].

- [38] M. Drewes, B. Garbrecht, D. Gueter and J. Klaric, *Leptogenesis from Oscillations of Heavy Neutrinos with Large Mixing Angles*, *JHEP* **12** (2016) 150 [[arXiv:1606.06690](#)] [[INSPIRE](#)].
- [39] J. Ghiglieri and M. Laine, *GeV-scale hot sterile neutrino oscillations: a derivation of evolution equations*, *JHEP* **05** (2017) 132 [[arXiv:1703.06087](#)] [[INSPIRE](#)].
- [40] A. Caputo, P. Hernández, J. Lopez-Pavon and J. Salvado, *The seesaw portal in testable models of neutrino masses*, *JHEP* **06** (2017) 112 [[arXiv:1704.08721](#)] [[INSPIRE](#)].
- [41] S. Eijima and M. Shaposhnikov, *Fermion number violating effects in low scale leptogenesis*, *Phys. Lett. B* **771** (2017) 288 [[arXiv:1703.06085](#)] [[INSPIRE](#)].
- [42] T. Asaka, S. Eijima, H. Ishida, K. Minogawa and T. Yoshii, *Initial condition for baryogenesis via neutrino oscillation*, *Phys. Rev. D* **96** (2017) 083010 [[arXiv:1704.02692](#)] [[INSPIRE](#)].
- [43] S. Eijima, M. Shaposhnikov and I. Timiryasov, *Freeze-out of baryon number in low-scale leptogenesis*, *JCAP* **11** (2017) 030 [[arXiv:1709.07834](#)] [[INSPIRE](#)].
- [44] S. Antusch et al., *Probing Leptogenesis at Future Colliders*, *JHEP* **09** (2018) 124 [[arXiv:1710.03744](#)] [[INSPIRE](#)].
- [45] S. Eijima, M. Shaposhnikov and I. Timiryasov, *Parameter space of baryogenesis in the ν MSM*, [arXiv:1808.10833](#) [[INSPIRE](#)].
- [46] R.E. Shrock, *Pure Leptonic Decays With Massive Neutrinos and Arbitrary Lorentz Structure*, *Phys. Lett.* **112B** (1982) 382 [[INSPIRE](#)].
- [47] R.E. Shrock, *Electromagnetic Properties and Decays of Dirac and Majorana Neutrinos in a General Class of Gauge Theories*, *Nucl. Phys. B* **206** (1982) 359 [[INSPIRE](#)].
- [48] R.E. Shrock, *General Theory of Weak Leptonic and Semileptonic Decays. 1. Leptonic Pseudoscalar Meson Decays, with Associated Tests For and Bounds on, Neutrino Masses and Lepton Mixing*, *Phys. Rev. D* **24** (1981) 1232 [[INSPIRE](#)].
- [49] R.E. Shrock, *General Theory of Weak Processes Involving Neutrinos. 2. Pure Leptonic Decays*, *Phys. Rev. D* **24** (1981) 1275 [[INSPIRE](#)].
- [50] M. Gronau, C.N. Leung and J.L. Rosner, *Extending Limits on Neutral Heavy Leptons*, *Phys. Rev. D* **29** (1984) 2539 [[INSPIRE](#)].
- [51] D. Gorbunov and M. Shaposhnikov, *How to find neutral leptons of the ν MSM?*, *JHEP* **10** (2007) 015 [Erratum *ibid.* **11** (2013) 101] [[arXiv:0705.1729](#)] [[INSPIRE](#)].
- [52] A. Atre, T. Han, S. Pascoli and B. Zhang, *The Search for Heavy Majorana Neutrinos*, *JHEP* **05** (2009) 030 [[arXiv:0901.3589](#)] [[INSPIRE](#)].
- [53] F.F. Deppisch, P.S. Bhupal Dev and A. Pilaftsis, *Neutrinos and Collider Physics*, *New J. Phys.* **17** (2015) 075019 [[arXiv:1502.06541](#)] [[INSPIRE](#)].
- [54] LHCb collaboration, *Search for Majorana neutrinos in $B^- \rightarrow \pi^+ \mu^- \mu^-$ decays*, *Phys. Rev. Lett.* **112** (2014) 131802 [[arXiv:1401.5361](#)] [[INSPIRE](#)].
- [55] CMS collaboration, *Search for heavy Majorana neutrinos in $\mu^\pm \mu^\pm + \text{jets}$ events in proton-proton collisions at $\sqrt{s} = 8$ TeV*, *Phys. Lett. B* **748** (2015) 144 [[arXiv:1501.05566](#)] [[INSPIRE](#)].
- [56] ATLAS collaboration, *Search for heavy Majorana neutrinos with the ATLAS detector in pp collisions at $\sqrt{s} = 8$ TeV*, *JHEP* **07** (2015) 162 [[arXiv:1506.06020](#)] [[INSPIRE](#)].

- [57] CMS collaboration, *Search for heavy neutral leptons in events with three charged leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV*, *Phys. Rev. Lett.* **120** (2018) 221801 [[arXiv:1802.02965](#)] [[INSPIRE](#)].
- [58] A. Izmaylov and S. Suvorov, *Search for heavy neutrinos in the ND280 near detector of the T2K experiment*, *Phys. Part. Nucl.* **48** (2017) 984 [[INSPIRE](#)].
- [59] SHiP collaboration, *Prospects of the SHiP and NA62 experiments at CERN for hidden sector searches*, *PoS(NuFact2017)* **139** (2017) [[arXiv:1712.01768](#)] [[INSPIRE](#)].
- [60] NA62 collaboration, *Search for heavy neutral lepton production in K^+ decays*, *Phys. Lett. B* **778** (2018) 137 [[arXiv:1712.00297](#)] [[INSPIRE](#)].
- [61] BELLE collaboration, *Search for heavy neutrinos at Belle*, *Phys. Rev. D* **87** (2013) 071102 [Erratum *ibid.* **D 95** (2017) 099903] [[arXiv:1301.1105](#)] [[INSPIRE](#)].
- [62] HERA-B collaboration, *Measurement of D^0 , D^+ , D_s^+ and D^{*+} Production in Fixed Target 920 GeV Proton-Nucleus Collisions*, *Eur. Phys. J. C* **52** (2007) 531 [[arXiv:0708.1443](#)] [[INSPIRE](#)].
- [63] C. Lourenco and H.K. Wohri, *Heavy flavour hadro-production from fixed-target to collider energies*, *Phys. Rept.* **433** (2006) 127 [[hep-ph/0609101](#)] [[INSPIRE](#)].
- [64] SHiP collaboration, *Heavy Flavour Cascade Production in a Beam Dump*, [CERN-SHiP-NOTE-2015-009](#).
- [65] SHiP collaboration, *SHiP sensitivity to Heavy Neutral Leptons*, [CERN-SHiP-NOTE-2016-003](#).
- [66] S.N. Gninenko, D.S. Gorbunov and M.E. Shaposhnikov, *Search for GeV-scale sterile neutrinos responsible for active neutrino oscillations and baryon asymmetry of the Universe*, *Adv. High Energy Phys.* **2012** (2012) 718259 [[arXiv:1301.5516](#)] [[INSPIRE](#)].
- [67] K. Bondarenko, A. Boyarsky, D. Gorbunov and O. Ruchayskiy, *Phenomenology of GeV-scale Heavy Neutral Leptons*, *JHEP* **11** (2018) 032 [[arXiv:1805.08567](#)] [[INSPIRE](#)].
- [68] SHiP collaboration, *Mass dependence of branching ratios into HNL for FairShip*, [CERN-SHiP-NOTE-2016-001](#).
- [69] M. Al-Turany et al., *The FairRoot framework*, *J. Phys. Conf. Ser.* **396** (2012) 022001 [[INSPIRE](#)].
- [70] T. Sjöstrand, S. Mrenna and P.Z. Skands, *A Brief Introduction to PYTHIA 8.1*, *Comput. Phys. Commun.* **178** (2008) 852 [[arXiv:0710.3820](#)] [[INSPIRE](#)].
- [71] GEANT4 collaboration, *GEANT4: A Simulation toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250 [[INSPIRE](#)].
- [72] C. Andreopoulos et al., *The GENIE Neutrino Monte Carlo Generator*, *Nucl. Instrum. Meth. A* **614** (2010) 87 [[arXiv:0905.2517](#)] [[INSPIRE](#)].
- [73] T. Sjöstrand, S. Mrenna and P.Z. Skands, *PYTHIA 6.4 Physics and Manual*, *JHEP* **05** (2006) 026 [[hep-ph/0603175](#)] [[INSPIRE](#)].
- [74] SHiP collaboration, *Simulation and pattern recognition for the SHiP Spectrometer Tracker*, [CERN-SHiP-NOTE-2015-002](#).
- [75] SHiP collaboration, *Particle Identification tools and performance in the SHiP Experiment*, [CERN-SHiP-NOTE-2017-002](#).

- [76] A.D. Dolgov, S.H. Hansen, G. Raffelt and D.V. Semikoz, *Heavy sterile neutrinos: Bounds from big bang nucleosynthesis and SN1987A*, *Nucl. Phys. B* **590** (2000) 562 [[hep-ph/0008138](#)] [[INSPIRE](#)].
- [77] O. Ruchayskiy and A. Ivashko, *Restrictions on the lifetime of sterile neutrinos from primordial nucleosynthesis*, *JCAP* **10** (2012) 014 [[arXiv:1202.2841](#)] [[INSPIRE](#)].
- [78] NA62 collaboration, *Searches for very weakly-coupled particles beyond the Standard Model with NA62*, in *Proceedings, 13th Patras Workshop on Axions, WIMPs and WISPs, (PATRAS 2017)*, Thessaloniki, Greece, 15–19 May 2017, pp. 145–148 (2018) [[DOI:10.3204/DESY-PROC-2017-02/dobrich.babette](#)] [[arXiv:1711.08967](#)] [[INSPIRE](#)].
- [79] K.-m. Cheung, *B_c meson production at the Tevatron revisited*, *Phys. Lett. B* **472** (2000) 408 [[hep-ph/9908405](#)] [[INSPIRE](#)].
- [80] LHCb collaboration, *Observation of $B_c^+ \rightarrow D^0 K^+$ decays*, *Phys. Rev. Lett.* **118** (2017) 111803 [[arXiv:1701.01856](#)] [[INSPIRE](#)].
- [81] LHCb collaboration, *Measurement of b-hadron production fractions in 7 TeV pp collisions*, *Phys. Rev. D* **85** (2012) 032008 [[arXiv:1111.2357](#)] [[INSPIRE](#)].
- [82] A.V. Berezhnoy, A.K. Likhoded and O.P. Yushchenko, *Some features of the hadronic $B_c^{(*)}$ meson production at large p_T* , *Phys. Atom. Nucl.* **59** (1996) 709 [[hep-ph/9504302](#)] [[INSPIRE](#)].
- [83] A.V. Berezhnoy, *Color flows for the process $gg \rightarrow B_c + c + \bar{b}$* , *Phys. Atom. Nucl.* **68** (2005) 1866 [[hep-ph/0407315](#)] [[INSPIRE](#)].
- [84] C.-H. Chang, C.-F. Qiao, J.-X. Wang and X.-G. Wu, *The Color-octet contributions to P-wave B_c meson hadroproduction*, *Phys. Rev. D* **71** (2005) 074012 [[hep-ph/0502155](#)] [[INSPIRE](#)].
- [85] A.V. Berezhnoy, A.K. Likhoded and A.A. Martynov, *Associative Production of B_c and D Mesons at LHC*, *Phys. Rev. D* **83** (2011) 094012 [[arXiv:1011.1555](#)] [[INSPIRE](#)].
- [86] K. Kolodziej, A. Leike and R. Ruckl, *Production of B_c mesons in hadronic collisions*, *Phys. Lett. B* **355** (1995) 337 [[hep-ph/9505298](#)] [[INSPIRE](#)].
- [87] K. Kolodziej and R. Ruckl, *On the energy dependence of hadronic B_c production*, *Nucl. Instrum. Meth. A* **408** (1998) 33 [[hep-ph/9803327](#)] [[INSPIRE](#)].
- [88] C.-H. Chang, C. Driouichi, P. Eerola and X.G. Wu, *BCVEGPY: An Event generator for hadronic production of the B_c meson*, *Comput. Phys. Commun.* **159** (2004) 192 [[hep-ph/0309120](#)] [[INSPIRE](#)].
- [89] M. Cacciari, M. Greco and P. Nason, *The p_T spectrum in heavy flavor hadroproduction*, *JHEP* **05** (1998) 007 [[hep-ph/9803400](#)] [[INSPIRE](#)].
- [90] M. Cacciari, S. Frixione and P. Nason, *The p_T spectrum in heavy flavor photoproduction*, *JHEP* **03** (2001) 006 [[hep-ph/0102134](#)] [[INSPIRE](#)].
- [91] SHiP collaboration, *HNL sensitivity of SHiP experiment*, <https://zenodo.org/record/1472071>.